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AIRCRAFT-BORNE INFRARED MEASUREMENTS

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Infrared measurements of natural and induced infrared sources were measured. The measurements included: near infrared atmospheric measurements in an auroral region with radiometers in the 1.7 µm and 2.8 µm region; infrared measurements of aircraft emissions and reflections in the 2.5 to 7.5 µm spectral region; and spectral measurements of the airglow emissions produced by fundamental hydroxyl chemiluminescent processes in

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the upper atmosphere. All of the measurements were made from AFGL's NKC-135A ~~S/N 53120~~ aircraft.

To accomplish the measurements it was necessary to modify, maintain, calibrate, and operate various interferometer and radiometer systems. Processing and reduction of the data were also major efforts which were necessary to allow proper presentation of the measurements in scientific reports. The data reduction techniques were continually improved to efficiently provide the desired graphs and tables. An important advancement was made in the spatial radiometer data reduction process. A system was designed and techniques were developed which enable one to accurately calibrate the spatial data taken with the existing AFGL spatial radiometers. Citations are provided to

The measured data and significant hardware advances which have been presented in scientific reports and open literature. References to these reports are given herein.

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ACKNOWLEDGEMENTS

The Defense Nuclear Agency and Defense Advanced Research Projects Agency sponsored the research covered by this contract. The efforts were defined and monitored by AFGL. The continued support of these agencies was greatly appreciated.

Several employees of the Electro-Dynamics Laboratories (EDL) were instrumental in the completion of the contractual efforts. Supervision of the efforts was performed by Ronald J. Huppi and Doran J. Baker. Engineering and field measurement support were provided by Randy B. Shipley, Larry B. Smith, Dr. John H. Schummers, Brent Bartschi, Roy W. Esplin and Ronald J. Huppi. Thomas Hudson IV provided laboratory technician support. Data reduction and analysis efforts were accomplished by Ronald J. Huppi, John H. Schummers, Gene Ware and Charles Eastman. In addition, the complete EDL team was available for consultation providing great depth for solving the required problems.

The authors would also like to recognize the direction given by Brian P. Sandford and Dr. A.T. Stair of AFGL. Their guidance and interest in the efforts were appreciated.

SUMMARY

Under this contract Utah State University (USU) has planned and performed spectral measurements of natural and induced background and target sources, maintained and improved radiometer and interferometer instrumentation, and performed data reduction and analysis on measured data. Measured data and instrumentation descriptions have been presented in AFGL reports and open literature. This report summarizes the contractual work which was performed and the reports which were written. The applicable reports include three scientific reports (*Huppi and Baker* [1976], *Huppi* [1976], *Huppi and Reed* [1977]) and a series of reports co-authored with AFGL/Optical Physics Division, *Sandford et al.* [1976a, 1976b, 1976c, 1976d, 1977a, 1977b]. The measurements are a continuation of those performed on contract number F19628-73-C-0302 which was previously completed by USU.

The major contractual efforts have been as follows:

1. Near infrared measurements in the auroral region were made with radiometers in the 1.70 μm and 2.8 μm regions.

2. An existing USU radiometer was modified to operate as part of the NIR radiometer system in the aircraft in the 2.0 to 7.5 μm spectral region.

3. Infrared measurements of aircraft emissions and reflections from 2.5 μm to 7.5 μm were made with the four channel NIR radiometer.

4. Interferometric spectral measurements of the hydroxyl fundamental region were made of the atmosphere with the Type III interferometer system.

5. Periodic calibrations and inspections were made of the radiometers and the interferometer systems.

6. A data reduction system was designed for the AFGL spatial radiometers.

7. Scientific reports and open literature reports were written and published.

NEAR INFRARED MEASUREMENTS IN THE AURORAL REGION

Significant infrared emission enhancements in the 2.75 to 3.04 μm region were measured from the AFGL NKC 135A aircraft while viewing an aurorally excited atmosphere with a radiometer. The measured enhancements occurred while viewing all types of auroral forms during the 1975 and 1976 ICECAP measurement program, and they became significant with respect to the night sky background emissions whenever the N_2^+ emissions at 3914A exceeded about 20 kiloRayleighs.

The 2.75 to 3.04 μm measurements were made with the Type III interferometer-radiometer system. A layout of the instrument system is shown in Figure 1. The system consists of an uncooled radiometer which is operated behind a liquid nitrogen cooled chopper. The cold chopper modulates the incoming atmospheric emissions and provides a cold reference source for the radiometer. As the chopper spins an alternating signal is seen by the radiometer which is due almost entirely to the emissions from the atmosphere. The chopper is mounted outside the aircraft with all the windows and the radiometer components mounted inside. Therefore, the thermal emissions from the window and radiometer components are not chopped and they do not contribute to the alternating signal. Thus, only the atmospheric emissions are detected when the alternating signal of the radiometer is synchronously demodulated using a reference signal from the chopper.

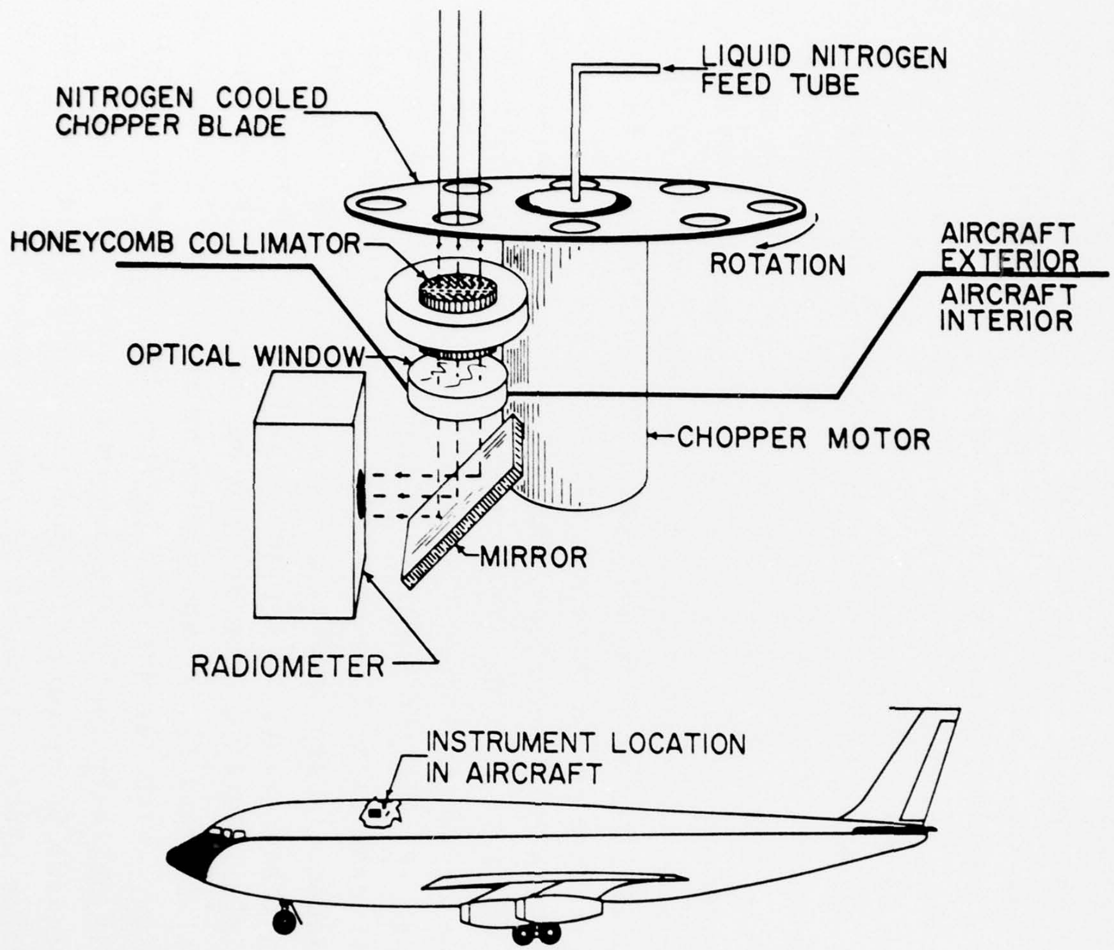


Figure 1. Liquid nitrogen cooled chopper and radiometer system.

In addition to the cold chopper-radiometer system, three other instrument systems were operated to provide additional monitors of the atmospheric conditions. They included the NIR radiometer developed by *Huppi* [1977], a 3914A photometer and an all-sky camera operated by Photometrics, Inc. All of the instruments were co-aligned and looked vertically out of the aircraft with identical fields of view. A summary of the specifications of all the instruments is given in Table 1.

Scientific Report No. 3, which was a contractual effort, presents and analyzes the data measured by the instrumentation, *Huppi and Reed* [1977]. An example of typical data which was measured on March 7, 1976 is shown in Figure 2. From top to bottom the figure gives the latitude location of the aircraft, the longitude location of the aircraft, the air temperature at the aircraft altitude, the aircraft altitude, the 3914A (N_2^+) emissions, the 2.94 μm infrared emissions, and the 1.70 μm (OH, $\Delta V=2$) emissions. Expanded plots of three of the enhancement periods are shown in Figures 3,4, and 5. Within the angular resolution capabilities of the instrumentation, the measured 2.75 to 3.04 μm (2.94 μm) enhancements appeared to co-vary spatially and temporally with enhancements in the ionization prompt fluorescence of the N_2^+ at 3914A. However, the enhancements did not correlate with the (5,3) band of the hydroxyl $\Delta V'=2$ sequence at 1.7 μm, which was measured by the NIR radiometer. Therefore, it is unlikely that the enhancements were the result of increases in hydroxyl fundamental sequences due to perturbed airglow processes, since one would expect the fundamental hydroxyl emissions in the 2.75 to 3.04 μm region to behave similar to the overtone emissions as given by *Baker* [1976]. It is suggested by *Huppi and Reed* [1977] and *Stair et al.* [1975] that first overtone nitric oxide is the most probable source creating the enhanced infrared emissions.

TABLE 1. Instrument specifications for 1975 and 1976 ICE CAP airborne measurements.

Instrument/Year	Field of View (Degrees Circular)	Spectral Response (μm)		Noise Equivalent Radiance*(kiloRayleighs RMS)
		Center λ	Δλ(50%)	
Type III Radiometer				
1975	10	2.83	.155	3.9
1976	10	2.94	.20	6.0
1976	5	2.76	.56	9.0
NIR Radiometer 1975 & 1976	10	1.70	.07	1.0
Photometer				
1975	10	.3914	.0014	.007**
1976	10	.3914	.0014	.007**
1976	5	.3914	.0014	.010**
All Sky Camera 1975 & 1976	165	Film	Film	N/A

* Measured for a noise equivalent bandwidth of .03 hz.

** Noise level is limited by the dark current of the photomultiplier tube.

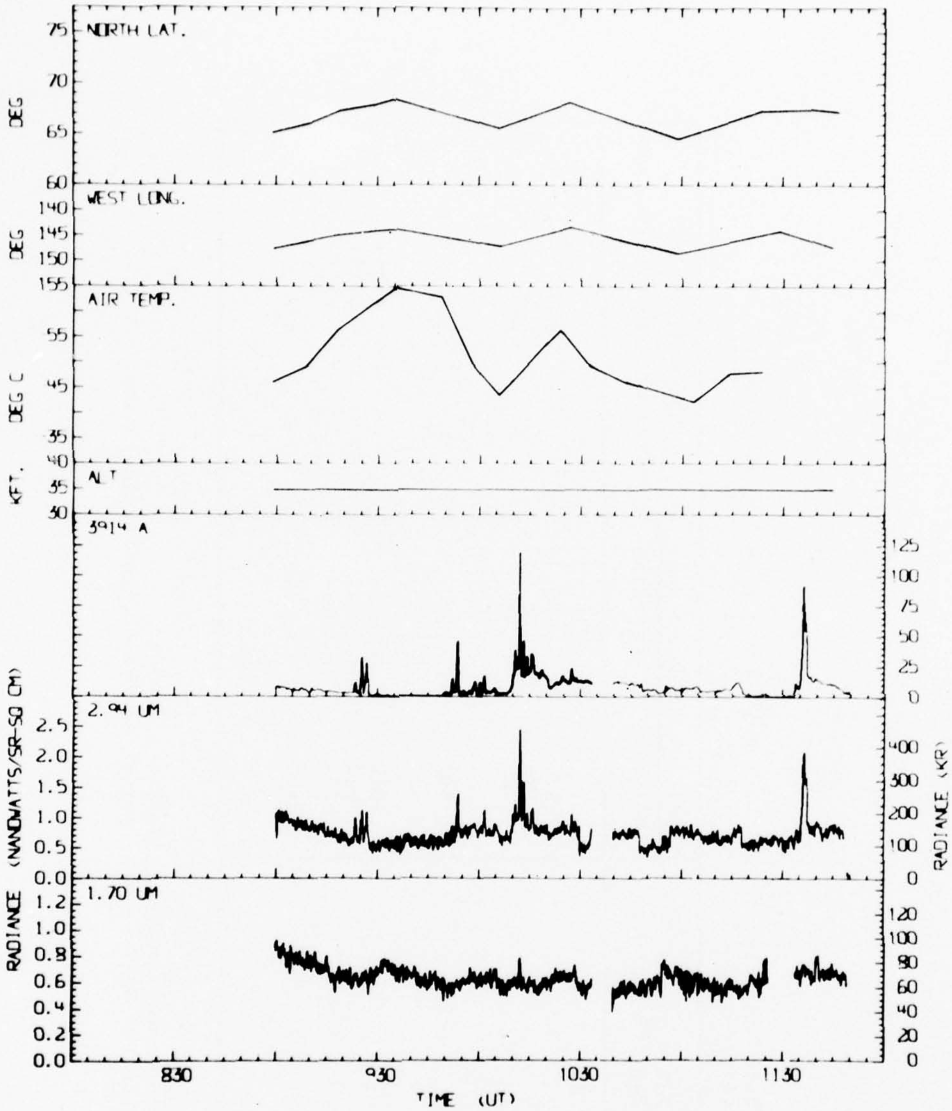


Figure 2. Measurements made with aircraft-borne instrumentation on March 7, 1976 showing significant infrared enhancements which are correlated with aurora.

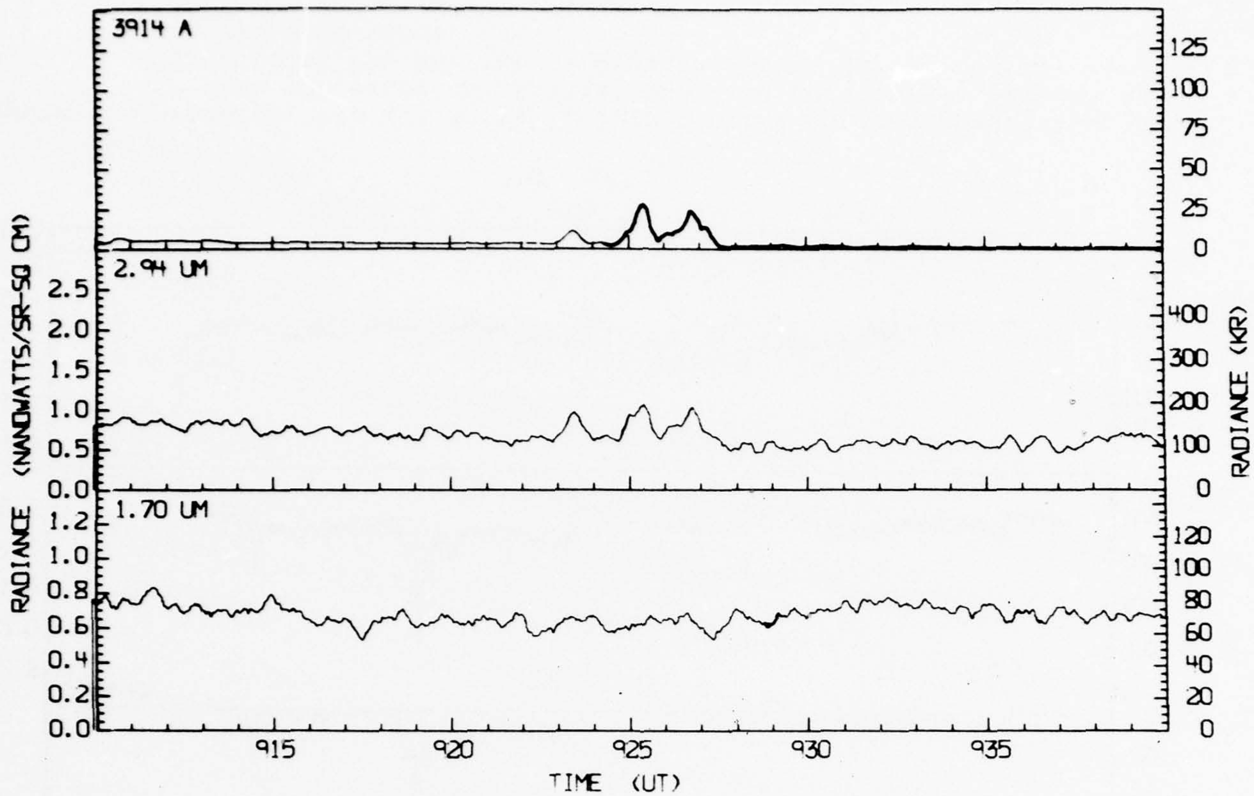


Figure 3. Measured data for March 7, 1976 plotted on an expanded time scale to show the correlation between the 2.94 μm emissions and the 3914A emissions during a period when small enhancements occurred.

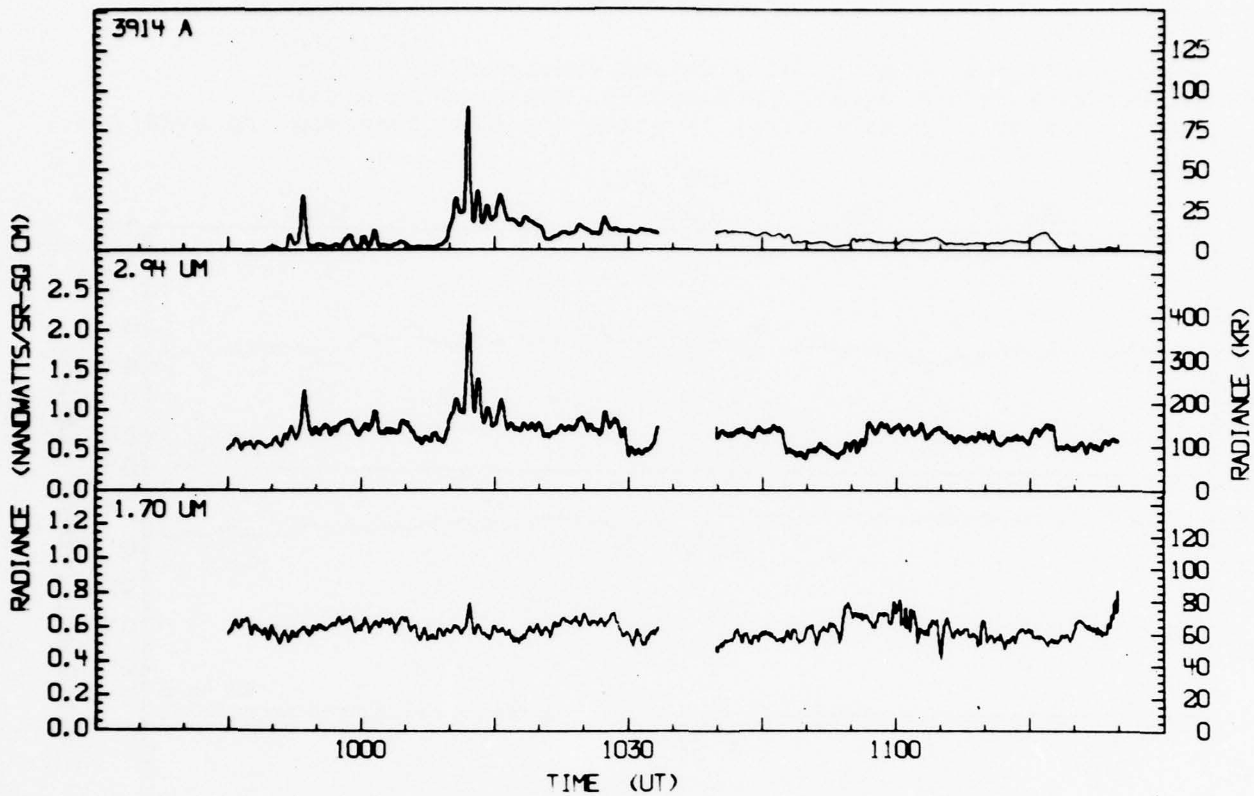


Figure 4. Measured data for March 7, 1976 plotted on an expanded time scale to show the excellent spatial and time correlation between the 3914A emissions and the 2.94 μm emissions during rapidly fluctuating auroral conditions.

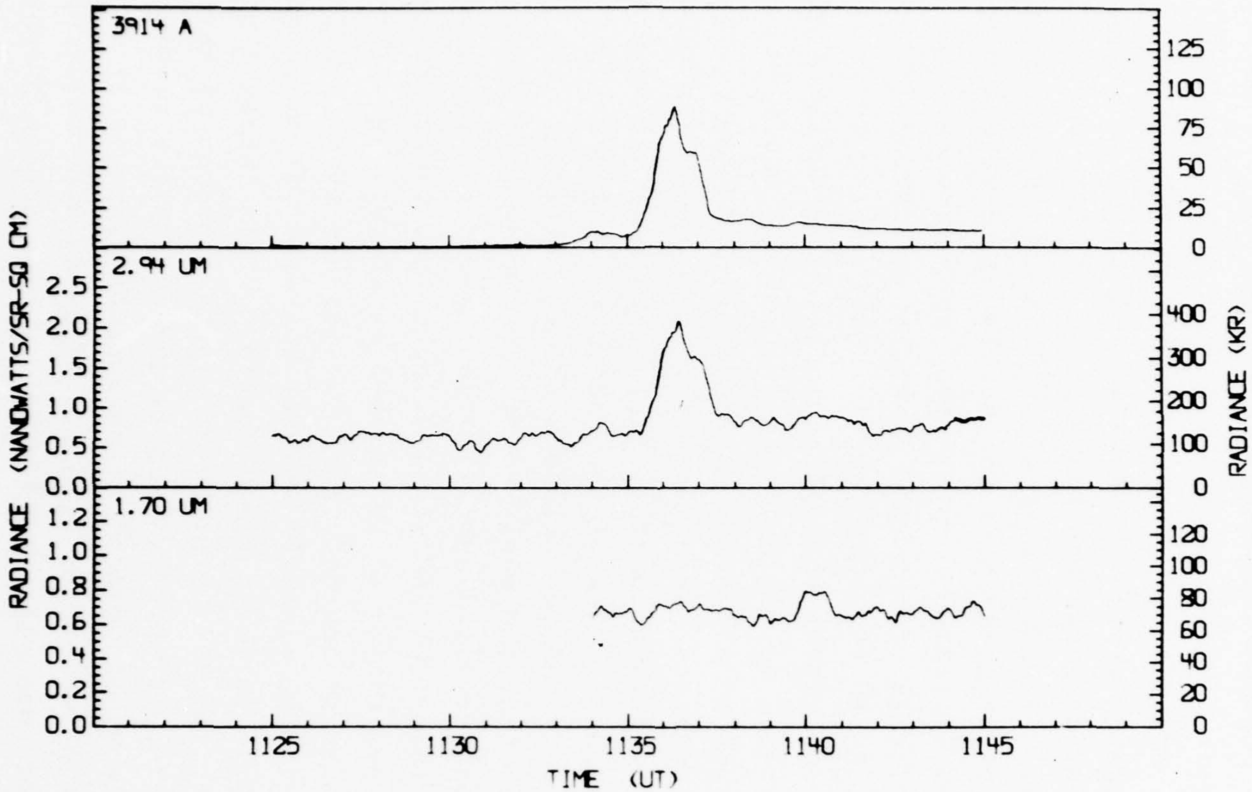


Figure 5. Measured data for March 7, 1976 plotted on an expanded time scale to illustrate the correlation between the 3914A emissions and the 2.94 μm emissions during a period when a large enhancement occurred.

NIR RADIOMETER MODIFICATION

A four channel radiometer, which was constructed using the techniques given in Scientific Report No. 2 by *Huppi* [1976], was modified to operate as part of the NIR aircraft-borne radiometer system. The basic radiometer including optics and electronics was existant in USU's inventory of instruments. In order to apply the radiometer to the Teal Ruby measurement program it was necessary to make modifications to the instrument. Provisions were made to allow spectral coverage from 2.0 to 7.5 μm, to match the instrument fields of view to the measurement requirements, and to allow aiming the instrument through an infrared germanium window.

A pictorial of the head assembly of the modified radiometer is shown in Figure 6. As shown in the figure, an infrared viewer made by Hughes Aircraft Company was mounted to the top of the radiometer. This viewer was co-aligned with the fields of view of the radiometer channels, and it was modified by USU to include an aiming reticle. The optical layout of the modified infrared viewer is shown in Figure 7, and detailed specifications are given in Table 2. The image properties and sensitivity of the viewer allow the radiometer and viewer to be tracked on almost any object or infrared emission source. This is possible even through a germanium window, since the viewer converts infrared images which transmit through germanium, to visible images that can be seen with the eye. During many data missions we have found that the infrared viewer is sufficient for viewing and tracking almost all practical measurement sources of interest.

The main radiometer consists of four independent optical and detector channels, which make use of a common chopper. Figure 8 shows an optical and electrical layout which is representative of each channel. The collecting lens, L_1,

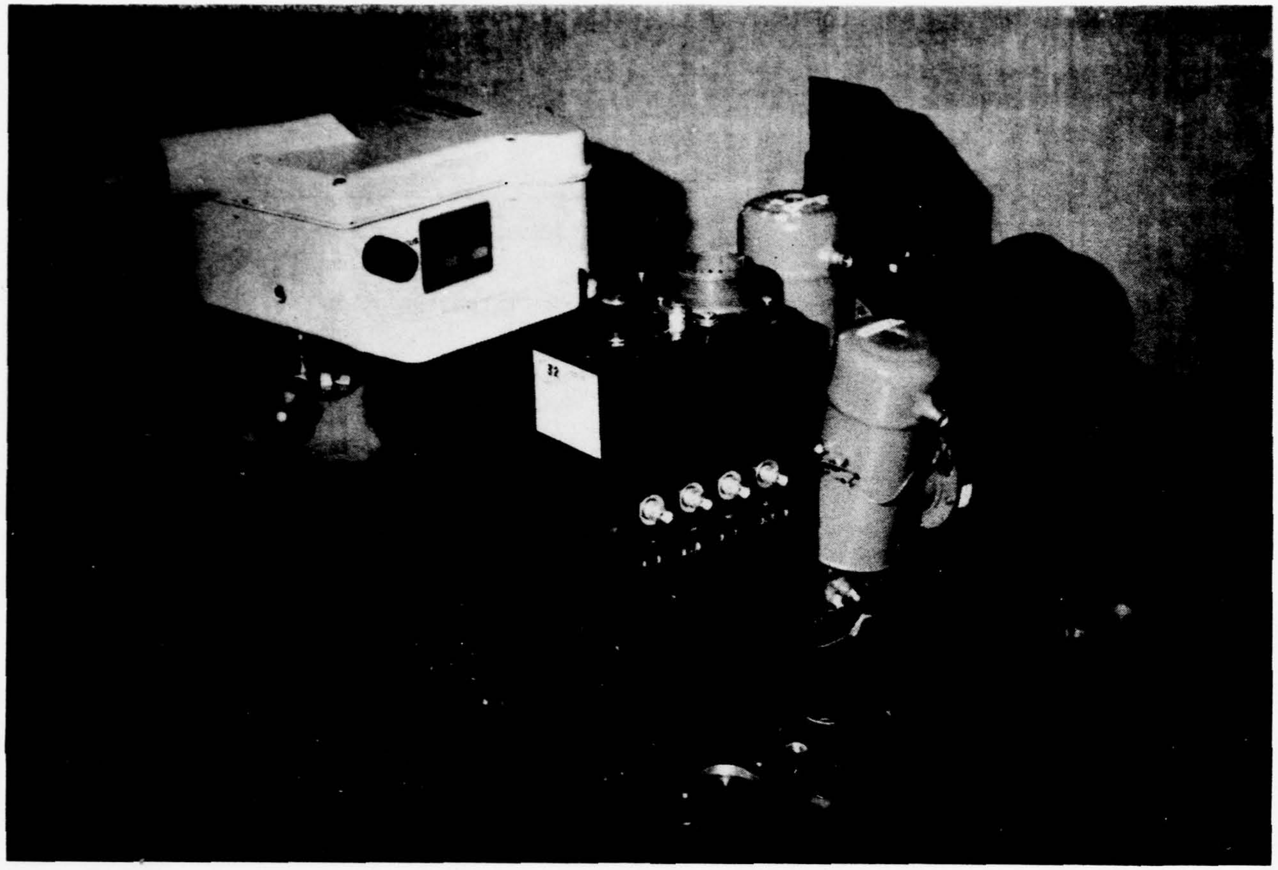


Figure 6. Pictorial of the head assembly of the modified radiometer.

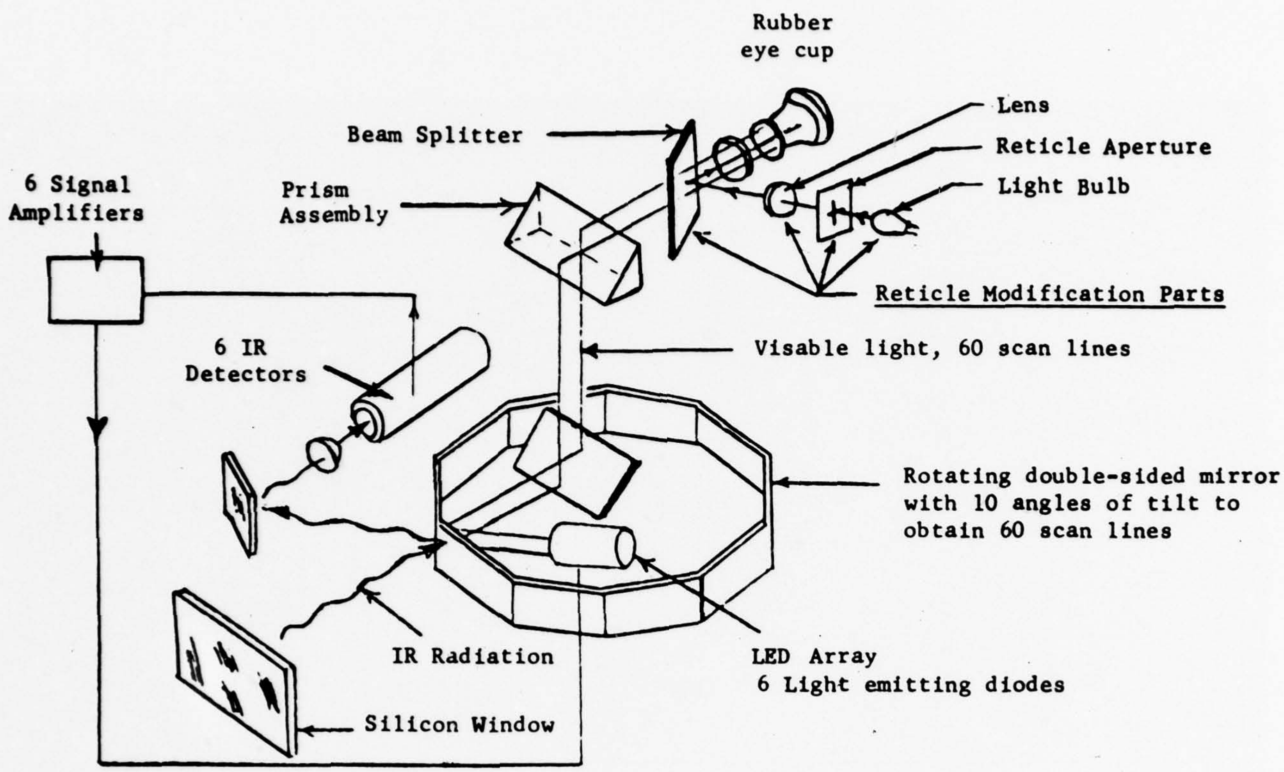
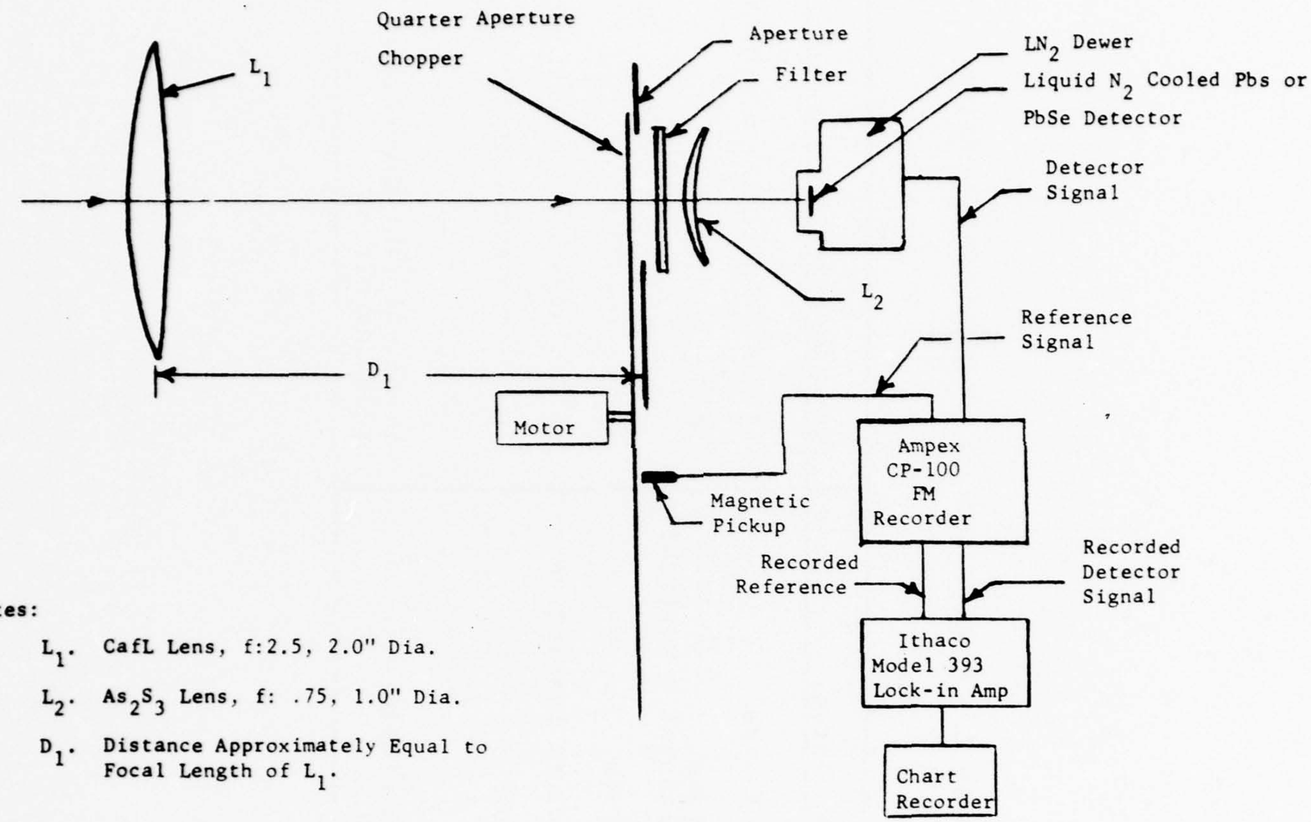


Figure 7. Infrared viewer used for aiming the four channel radiometer.

Table 2. Probeye Infrared Viewer Specifications

Characteristics	Specifications
Field of view	18^{o} horizontal x 7.5^{o} vertical
Resolution (horizontal & vertical)	$.12^{o}$
Frame rate	15 per second
Temperature resolution	$.5^{o}C$ minimum
Detector	InSb (6 element array)
Weight	7.2 lb.
Viewing display	Light emitting diodes and scanning mirror



Notes:

- **L_1.** **CafL Lens**, f:2.5, 2.0" Dia.
- **L_2.** **As_2S_3 Lens**, f: .75, 1.0" Dia.
- **D_1.** **Distance Approximately** Equal to **Focal Length** of L_1.

Figure 8. Optical and electrical layout of the four channel radiometer.

focuses incident radiation on the aperture. The energy that passes through this aperture is optically filtered with a changeable interference filter and is collected by lens, L_2. Lens, L_2, then focuses the energy on a liquid nitrogen cooled detector.

Proper selection and integration of detectors into the system was one necessary modification which was made to the existing USU radiometer to facilitate the taking of measurements over the 2.0 to 7.5 μm range. Two PbS detectors were incorporated to cover the 2 to 4 μm region and two PbSe detectors were used to cover the 3.5 to 5 μm and 5 to 7 μm regions. All detectors were cooled to 77^{o}K. A summary of the instrument specifications using these detectors is given in Table 3.

The fields of view of the various channels of the radiometer were matched to individual measurement requirements. Fields of views ranging from $.5^{o} \times .5^{o}$ to $2^{o} \times 8^{o}$ were used at various times. The fields of view are changed by modifying the aperture and chopper in the radiometer. Basically, the maximum field of view of a radiometer channel is defined by the size of the aperture, since sources at infinity are focused on the aperture plane (see Figure 8). The FOV defined by the aperture plate can be divided into smaller FOV's by selecting an optical chopper blade with smaller openings than the opening in the aperture plate. Thus, the chopper efficiently modulates only sources which are imaged in an area smaller than or equal to the selected chopper blade opening. Reticle chopping techniques described by *Huppi* [1976] were used to design and balance the blade and aperture openings such that the detector receives constant unmodulated radiation from the blade and instrument at all times during operation. When operated in this mode, the detector also receives constant and unmodulated signals from uniform sources which fill the complete aperture.

Table 3. Summary of The Four Channel Radiometer Specifications

Channel	Spectral Region Being Used	Detector Type	Detector Temperature	Detector D* (Peak, 350,1) cm x $Hz^{1/2}$/watt	Typical Minimum Detectable Irradiance for .1μm Spectral Band. Watts/cm^2
1	5μm to 7μm	Extended PbSe	$77^{\circ}K$	1.7×10^{10}	1.5×10^{-10}
2	3.5μm to 5μm	PbS	$77^{\circ}K$	1.7×10^{10}	3×10^{-11}
3	2μm to 4μm	PbS	$77^{\circ}K$	1.0×10^{11}	6.0×10^{-12}
4	2μm to 4μm	PbS	$77^{\circ}K$	1.0×10^{11}	6.0×10^{-12}

The minimum detectable signal level is not detector noise limited. The level is dependent on background balance and background subtraction capabilities. The values given are for low background conditions. If the background is more than 5000 times brighter than the values given in the table, the minimum detectable signal will be dependent on the background level.

If the signal is synchronously rectified using a reference signal from the blade, only modulated signals which are synchronized with the chopper will be detected at the output. Thus, unmodulated uniform backgrounds and thermal emissions from the instrument will not be detectable, but small sources which are modulated are detectable even in bright backgrounds. The radiometer operating in this mode has provided excellent time history measurements of the emissions from various small sources for the Teal Ruby measurement program.

RADIOMETER MEASUREMENTS OF AIRCRAFT EMISSIONS AND REFLECTIONS

Infrared emissions generated or reflected from various aircrafts during flight were monitored with the four channel radiometer from the AFGL NKC-135 flying laboratory. Typically twelve selectable spectral bands in the 2.5 to 7.5 μm range were monitored on each aircraft, as defined by *Sandford et al.* [1976a]. Time histories of the irradiances of the aircraft sources were measured for various power increases, power decreases, fixed power settings and aircraft maneuvers. Absolute irradiance numbers were obtained for the various power conditions. Specific radiometric measurements and supporting comparisons with the data from the AFGL interferometer-spectrometer and the thermal spatial scanners has been presented in co-authored reports by *Sandford et al.* [1976c , 1976d, 1977a, 1977b]. To accomplish comparison between the radiometric data and the interferometer spectral data, the spectra were integrated over the passbands of the radiometer. As verified in the reports, the radiometer measurements and interferometer measurements are in good agreement. Due to the classified nature of this data, no sample information is given here.

SPECTRAL MEASUREMENTS OF FUNDAMENTAL HYDROXYL ATMOSPHERIC EMISSIONS

A Michelson interferometer, referred to as the Type III-1, was used in conjunction with the liquid nitrogen cooled chopper system to measure the airglow emissions spectra resulting from chemiluminescent reactions of the fundamental hydroxyl (OH) sequences. Scientific Report No. 1, *Huppi and Baker* [1976], gives detailed information about the temporal and spatial variations of hydroxyl emissions. The measurements that will be reported here add to this study by providing a spectrum of the emissions. The measurements were made from the AFGL NKC-135A aircraft looking overhead.

The basic measurement set up is shown in Figure 9. As described by *Huppi* [1974], the interferometer operates at ambient temperatures inside the aircraft while the chopper acts as a cold reference and provides a method for distinguishing the atmospheric emissions from the thermal emissions of the instrument and aircraft structures. Using this measurement technique, sources with spectral radiances in the range of 10^{-9} to 10^{-8} watts/cm^2-ster-μm can be measured in the 2 to 3.5 μm region, thus providing a technique for measuring the OH fundamental sequences.

A measured spectrum of a portion of the OH fundamental region is shown in Figure 10. The spectrum was measured March 26, 1976, and was reduced by coadding about 30 minutes of data. The emission levels are relatively small; and therefore the signal to noise ratio is not large. However, a comparison of the measured spectrum with a synthetic hydroxyl model, as shown in Figure 11, makes it apparent that the measured emissions result from fundamental hydroxyl processes. In fact a considerable improvement in signal to

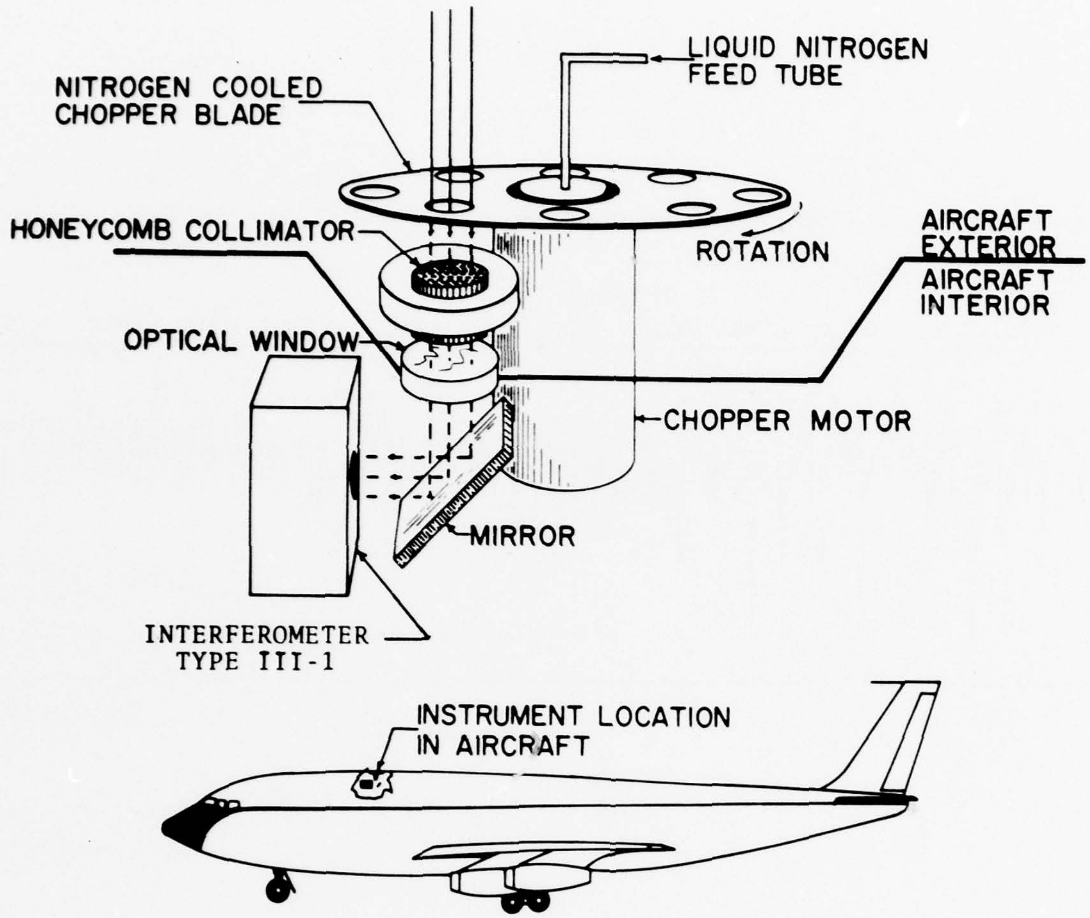


Figure 9. Liquid nitrogen cooled chopper and interferometer system.

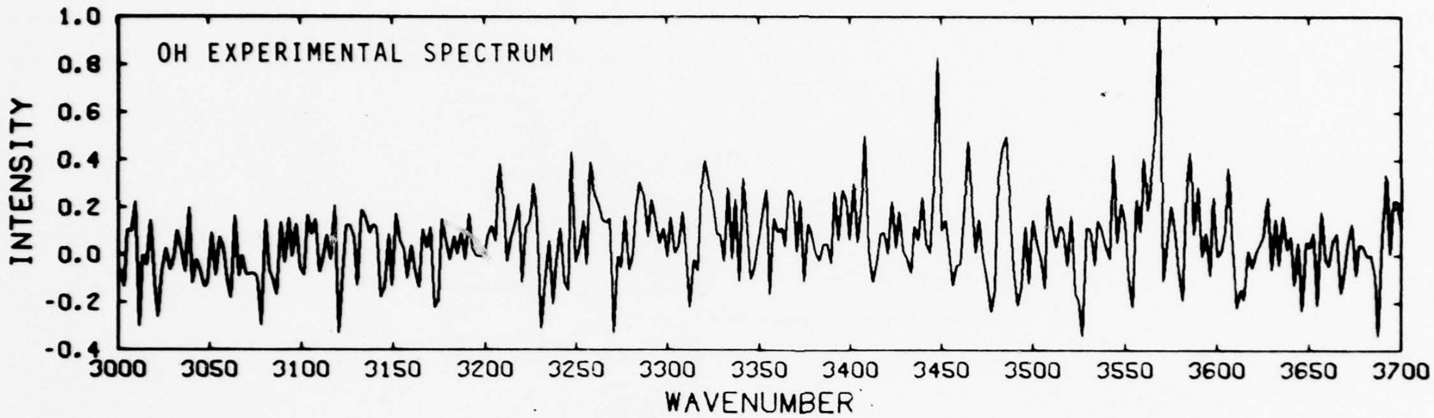


Figure 10. Fundamental hydroxyl spectrum measured on March 26, 1976 from the AFGL NKC-135 aircraft.

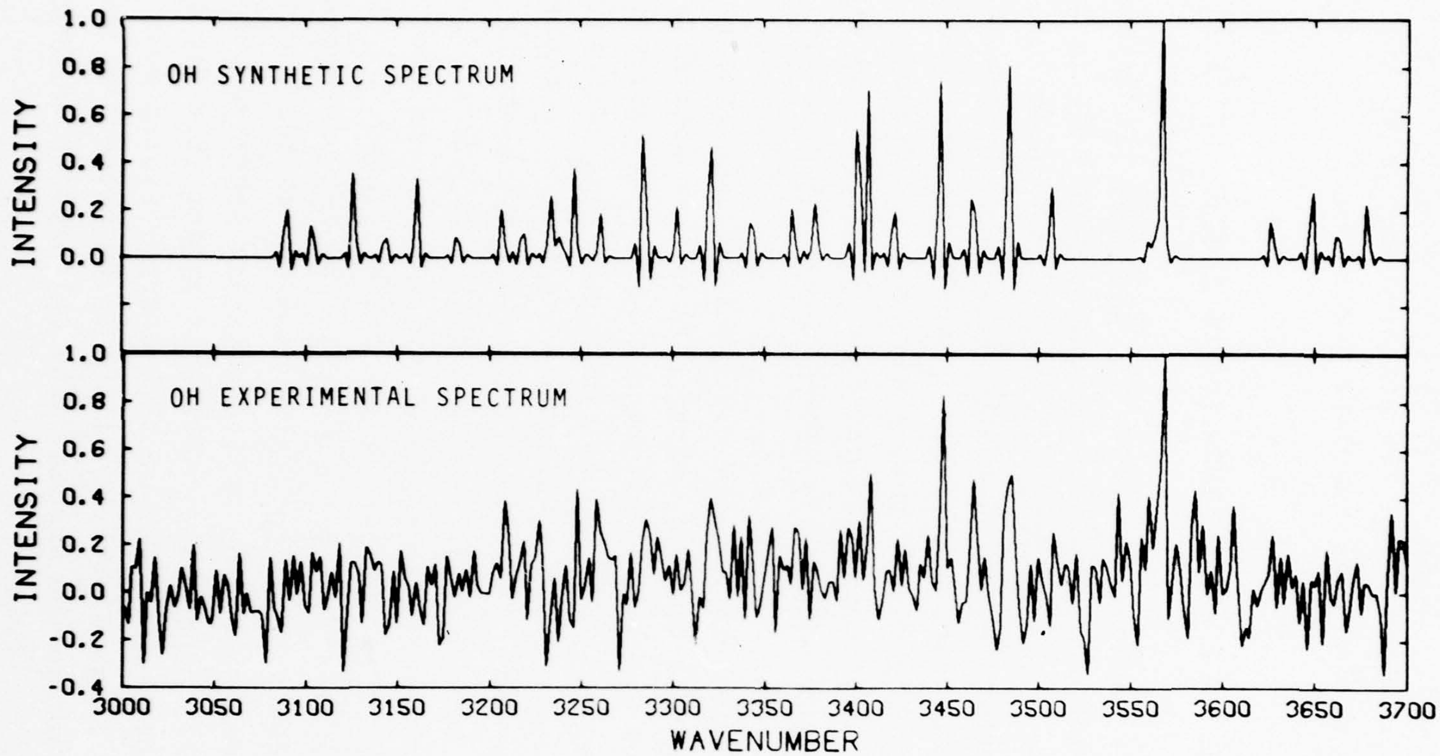


Figure 11. Comparison of measured hydroxyl spectrum with a synthetic spectrum.

noise can be gained through the use of correlation procedures which effectively compare the measured data with a synthetic model. Using a correlation technique *Huppi* [1978] has further verified that the measured emissions did indeed result from fundamental hydroxyl processes.

MAINTENANCE AND CALIBRATION OF INSTRUMENTATION

The NIR radiometer system and the Type III interferometer-radiometer system were maintained and kept in a state of readiness. The optical, electrical and mechanical parts were thoroughly inspected in the laboratory before and after each series of data missions. Inspections were also made during data flights and during each set of data missions. Parts were replaced as needed to insure proper operation of the instruments and to keep them in a constant state of readiness.

In addition to regular maintenance, each instrument was calibrated before and after each set of data missions. Calibrations were also performed on-board the aircraft during flight as necessary. The calibration methods described by *Sandford et al.* [1976a] were used for the radiometers and interferometers. Typically, laboratory calibrations are done using both a point source and an extended source. The inflight calibrations are done with an extended source which can be related to the laboratory calibrations.

In addition to the calibrations of the radiometers and interferometers, the Type III system has an added calibration problem, since the instruments are operated behind a cold optical chopper and collimator system (See Figures 1 and 9). The attenuation of this chopper system must be determined if absolute values are to be placed on data measured through the system. The calibration is complicated

by the fact that the attenuation of the collimator portion varies as a function of angle, and therefore, the throughput will vary when used with instruments having different fields of view.

The best way to calibrate the attenuation effect of the collimator is to perform a measurement using an extended source, the chopper system, and the actual radiometer or interferometer which is to be used. This process was performed for a radiometer for three field of view settings. The calibration set up is shown in Figure 12. As shown, a point source is chopped and sent into an integrating sphere. The sphere converts the point source to an extended source which is then measurable with the radiometer through the chopper system. During this process, the chopper blade is left in the open position. Then the chopper system is removed and the measurement is repeated. The ratio between the first and second measurement gives the integrated attenuation of the collimator and aperture for the specific field of view characteristics of the radiometer. Table 4 summarizes the attenuation of the chopper system for the three fields of views which were measured with the type III radiometer whose entrance aperture is partially vignetted by the chopper aperture. These values give a rough overview of typical attenuations for a practical radiometer with typical fields of view. To complete the calibration of the chopper system, the above results must be multiplied by the chopping efficiency of the rotating chopper. This efficiency can be readily calculated from the geometry of the system. The actual chopper blade modulates the incoming radiation in almost a sinusoidal fashion and has an efficiency of about 40%. This is only slightly less than an optimum square wave chopper which has an efficiency of 50%.

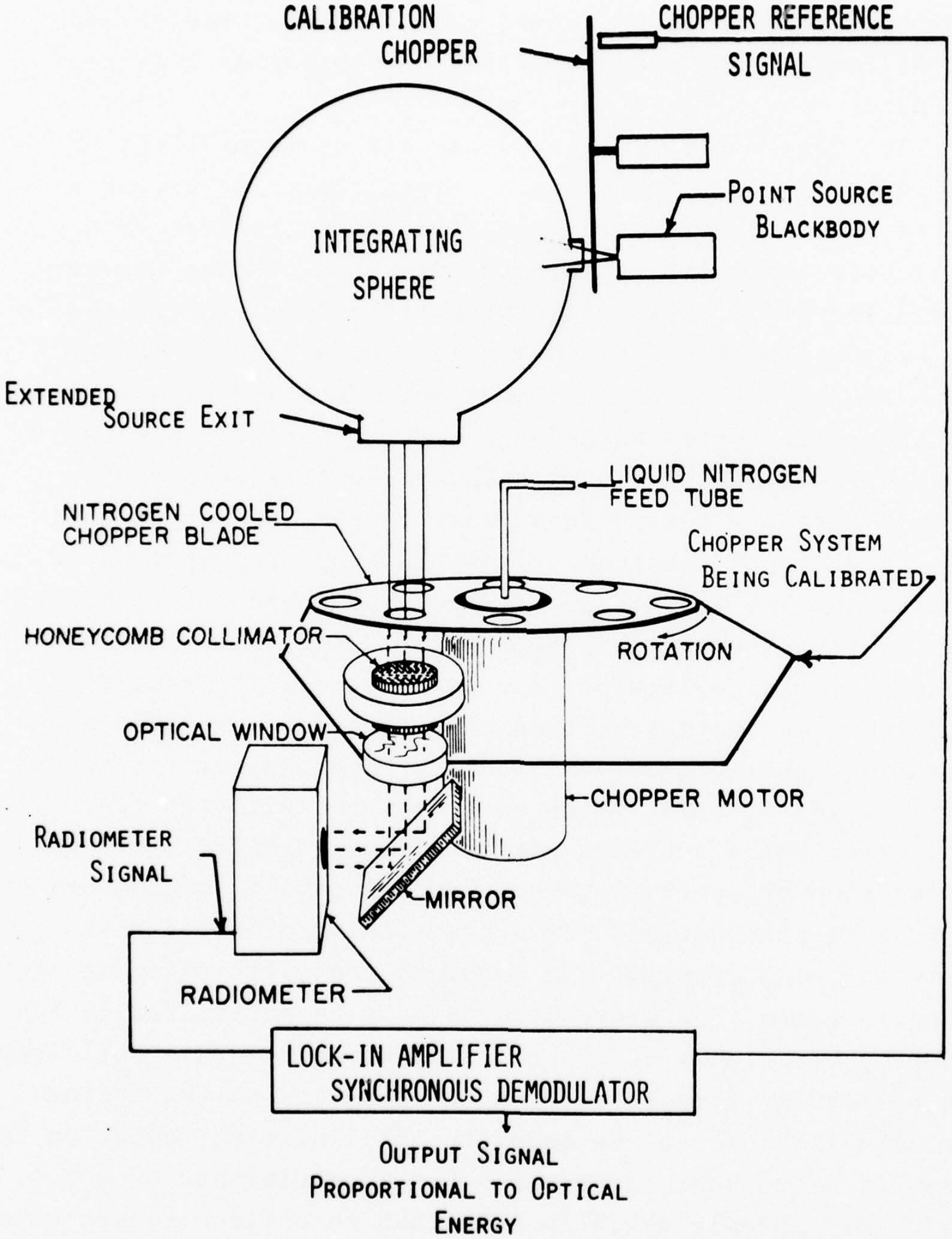


Figure 12. Calibration set up for the liquid nitrogen cooled chopper-collimator.

Table 4. Optical Transmissions of the Liquid N_2 Chopper System with Ca_2Fl and GE-106 Windows for Various Fields of View of Radiometers.

Field of View (Degrees)	Window Type	Measurement Wavelength (μm)	Window & Collimator Transmittance Unchopped (Percent)
10	Ca_2Fl	2.9	23.5
10	GE-106	2.9	19.1
5	Ca_2Fl	2.9	31.0
5	GE-106	2.9	28.7
2	Ca_2Fl	2.9	34.5
2	GE-106	2.9	31.0

SPATIAL DATA REDUCTION

One of the important efforts performed under this contract was the development of a system to quantitatively analyze spatial data that is being acquired by AFGL. Instrument parameters and illustrative data are contained in the reports by *Sandford et al.* [1976a,b,c,d, 1977a,b]. The analysis of the spatial data is valuable since it measures the spatial distribution of the infrared energy produced by a scene being viewed. For many problems, this spatial measurement may be of great importance in determining where the energy measured by spectral or radiometric instruments is distributed in their fields of view. It is also important for determining whether a localized target can be discriminated against various types of backgrounds.

A detailed description of the entire instrument and analysis system will be forthcoming as an AFGL technical report with joint AFGL and SRL authorship. In this section of this report, a brief overview will be given, covering the primary contributions that SRL make to this development program.

Several years ago, AFGL obtained an instrument system potentially capable of making accurate, quantitative measurements of the spatial distribution of infrared energy over a fairly wide field of view. Since this information was of secondary importance to that produced by spectral and temporal radiometers, the only analysis performed on the data was the making of qualitative pictures showing which portions of the field of view were emitting more infrared energy than the other portions. Accurate numeric measurements could not be made since the procedure involved making Polaroid snapshots of a CRT screen that was displaying the scene as measured by the instrument. The pictures did not contain

any reference measurements so that effective brightness could be compared to that produced by known radiance levels. Thus large changes in radiance levels from picture to picture were difficult to determine.

As the measurement programs at AFGL evolved, the spatial measurements greatly increased in importance. It became obvious that analysis procedures, and equipment to implement these procedures, were needed. Equipment was purchased by AFGL containing the necessary computing power, storage capacity, digital input and output, and graphic and pictorial display devices. Although this equipment was purchased by AFGL, a great deal of consultation with SRL personnel was performed to insure that all necessary equipment was available without raising the cost unnecessarily.

Once the equipment was obtained, the large task of designing and implementing the necessary procedures for accurate analysis of the spatial data had to be performed. As in the procurement of the data analysis equipment, the basic software was written by AFGL, but the procedures to be implemented, and the techniques to implement them, were determined largely through interaction and consultation with SRL.

The basic procedures for analyzing the spatial data are described in the following paragraphs. The first step is to determine basically what scene was being viewed as a function of time and which bandpass filters were used during a data collective run. This is done by monitoring various housekeeping functions and voice channels. Once the intervals of time to be analyzed have been determined, the computer can be commanded to digitize several infrared pictures and store them on a digital disc memory. Once a large number of pictures have been digitized, they are displayed on the pictorial display device. By careful examination of

each digitized picture, individual pictures can be selected for further processing, or in cases where the scene is stationary for several pictures, the pictures can be averaged for better signal to noise levels and then further processed.

The next step is to eliminate, as much as possible, any distortions introduced by the measurement system. The most important distortions introduced into the data are caused by the ac coupling of each detector in the instrument before the detectors are multiplexed together to form the analog video signal. This ac coupling was introduced to reduce the large amount of low frequency noise produced by the detectors, but it also eliminates the low frequency structure in the pictures. In the most general situation, the low frequencies cannot be re-inserted into the data; but under many circumstances, the appropriate low frequency signals can be assumed known, and higher frequencies boosted to compensate for the attenuation by the instrument. Other types of distortions can also be reduced. Since each detector is ac coupled independently the average level can shift due to differences in the scene from detector to detector. If however, all detectors see the same radiance during some part of the picture, they can be forced to agree in that region and thereby reduce the offsets in average level between detectors. If large noise spikes occur in certain spots, the picture can be filtered in small regions to eliminate or reduce the noise.

The remaining major procedures to be implemented are calibration and display. Once the response of each detector is known for each bandpass filter that was used, calibration of the data frame is reasonably straight forward. One difficulty arises when the filter passband is not flat and the spectral distribution of energy across the band is not uniform. The programs were written to allow the spectral

calibration to be used with an input spectral energy distribution, but in most cases neither is known accurately. In these cases, appropriate assumptions have to be made.

One of the most difficult problems encountered was to obtain calibrations of the detectors that were repeatable and stable with time. Many erroneous calibrations were performed due to high background levels that were not subtracted out, measurement procedures that were inadequate, or calibration signals that were not the necessary size and shape. These problems have been sorted out and accurate calibrations can now be made.

The last step to be discussed concerns storage and display of the corrected and calibrated pictures. Storage is important since many pictures are analyzed and comparisons between many pictures are desired. The storage problem was solved by giving each file a name that described its type, i.e., data or calibration, the bandpass filter used, and the time of measurement, and then storing it on the disc file storage area. Each picture can then be recovered, further processed or displayed at any time. An adequate display of the final results is a critical part of the analysis as well, since a proper type of display is necessary to pass the information on to the user. Calibrated pictorial display, contour plotting and perspective plotting are some of the display means currently available.

SCIENTIFIC REPORTS

The measured data and the data reduction performed under this contract led or contributed to reports. The reports are published as AFGL scientific reports or in the open literature. Three scientific reports were contractually required; however, as requested in the contract, additional reports and articles were written on the contractual efforts. The following is a detailed list of the publications:

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